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13. ABSTRACT (Maximum 200 words) It has been shown that the preferred technique for the growth of MODFET material is by MBE, since competing technologies have been unable to demonstrate a reproducible technique for the growth of these devices. However, MBE as a production technique has two major drawbacks: the capital investment is high, and the growth rate is slow.  Northeast Semiconductor's approach to the problem of increasing MBE throughput and reducing wafer cost is to use existing MBE systems to grow the same high quality material as is currently grown, but at a much faster pace. This required only a small modification of the molecular beam source. Research results have demonstrated that MODFET material can be grown at growth rates up to five times those currently used, with no degradation in electrical performance. This translates directly into cost savings for wafers grown.					
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Northeast Semiconductor, Inc.  
SBIR Phase 1 Final Report  
High Throughput MBE Materials for MODFETs  
U.S. Army Research Office,  
Contract #DAAL03-89-C-022

February 15, 1990

Program Objective

Semiconductor materials grown by the use of Molecular Beam Epitaxy (MBE) have superior device performance, but the material is expensive due to slow growth rate. The objective of the Phase I work was to demonstrate the feasibility of high-quality MBE growth at rates much faster than the present standard of 1 micrometer ( $\mu\text{m}$ ) per hour. MODFETs (GaAs/AlGaAs Modulation Doped Field Effect Transistors) were chosen for this growth study because their unique structure is very sensitive to variations in atomic constituents. Thus, the material quality, as a function of growth rate, can be accurately determined by measuring the electronic behavior of the MBE-grown structures. The objective of this study was obtained by showing that these structures can be grown at five times the usual rate with no degradation of material properties.

## Summary

It has been shown that the preferred technique for the growth of MODFET material is by MBE, since competing technologies have been unable to demonstrate a reproducible technique for the growth of these devices. However, MBE as a production technique has two major drawbacks: the capital investment is high, and the growth rate is slow.

A conventional MBE system, designed to produce one wafer at a time, costs roughly \$1Million. This one-wafer system, at conventional growth rates, will produce approximately 6-8 MODFET wafers per working shift. The market rate of this material is currently \$1K-\$2K per wafer. The high price of the material is a direct consequence of the necessity to recover the high initial investment, and the fact that only a few wafers can be produced per day, thus consuming long hours of machine time and process expendables.

The cost could be reduced by growing more than one wafer at a time, if the capital investment did not increase. But recently developed multi-wafer MBE systems cost more than twice as much as the conventional MBEs. These multi-wafer systems are unproven for the growth of high quality material and unknown in their reliability. If a multi-wafer system can grow three times the wafers per unit time as a conventional MBE, but has only 50 % up-time, the owner has lost considerable investment, and wafer costs will not drop.

Northeast Semiconductor's approach to the problem of increasing MBE throughput and reducing wafer cost is to use existing MBE systems to grow the same high quality material as is currently grown, but at a much faster pace. This required only a small modification of the molecular beam source.

As explained in the program results section of this final report, Northeast Semiconductor has demonstrated that MODFET material can be grown at growth rates up to five times those currently used, with no degradation in electrical performance. This translates directly into cost savings for wafers grown.

Most of Northeast Semiconductor's customers order MBE material in a lot size (6-10 wafers per lot). An average cost of one lot of material would be \$9K based upon a required growth time of one hour per wafer. Using the technology developed in this contract, the customer could receive 18-30 wafers for the same \$9K charge.



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## Program Results

All MODFET material consists of two basic domains, a high bandgap material which supplies electrons that "spill over" into a lower energy material which can be independently optimized for device performance. The material systems generally employed are  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  on GaAs,  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  on  $\text{In}_y\text{Ga}_{1-y}\text{As}$ , or  $\text{Al}_{.48}\text{In}_{.52}\text{As}$  on  $\text{Ga}_{.47}\text{In}_{.53}\text{As}$  (the subscripts refer to alloy percentages).

The material system chosen for this program was the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  on GaAs structure, as it is the most heavily studied and well understood. The structure used throughout this program was:

20 Å GaAs contact layer doped with Si to $2 \times (10)^{18} \text{ cm}^{-3}$
450 Å $\text{Al}_{.23}\text{Ga}_{.77}\text{As}$ layer doped with Si to $1.5 \times (10)^{18} \text{ cm}^{-3}$
50 Å $\text{Al}_{.23}\text{Ga}_{.77}\text{As}$ undoped spacer layer
1 $\mu\text{m}$ undoped GaAs buffer.
GaAs undoped high resistivity substrate

The Si atoms deposited in the AlGaAs layer give up electrons to the surrounding lattice. Electrons in AlGaAs are residing in a higher energy state than if they were in GaAs only. The electrons move into the GaAs, leaving behind their positively charged Si atom host. These electrons now residing in GaAs are free to move under less perturbation than if the Si atoms were in the same host material. The separation of the electrons from the atoms from which they came is what distinguishes a MODFET from other types of FETs.

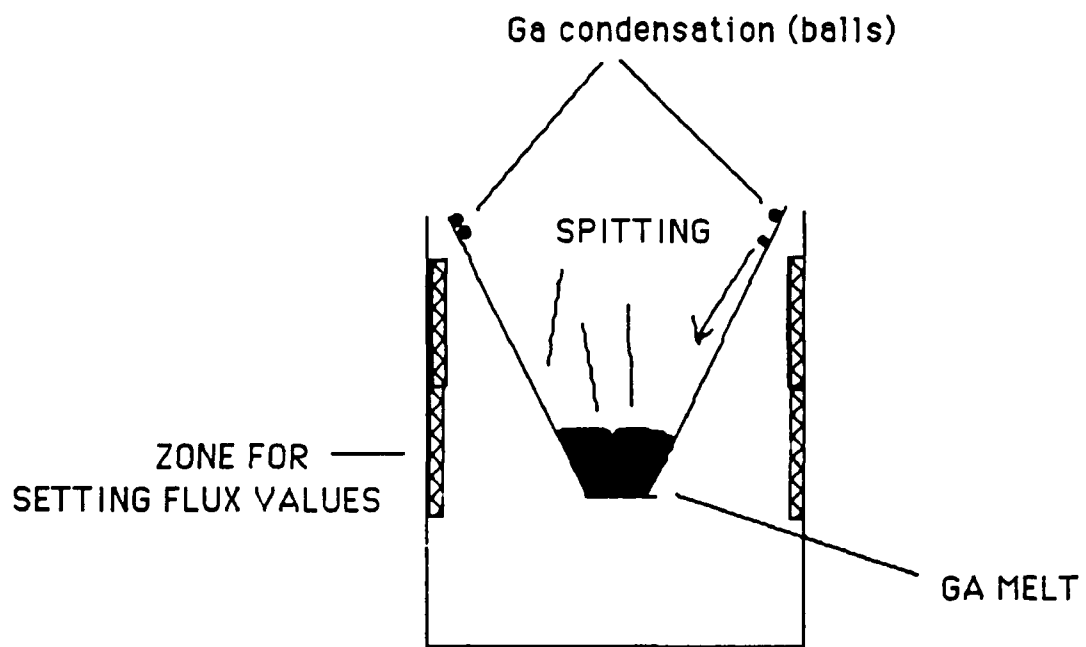
The structure listed above is identical to that which could be used in device processing with one exception: a MODFET layer used for FET fabrication would have a thicker contact layer. This thin-contact structure was designed for this study so that the electrical characteristics of the basic MODFET structure could be measured without interference from the sheet conductance of the GaAs contact.

To establish a base line for comparison, the material was first grown at conventional growth rates of 1  $\mu\text{m/hr}$  for the GaAs and 1.29  $\mu\text{m/hr}$  for the AlGaAs. The material was grown in a Varian GEN II MBE system using standard Varian effusion cells. All MODFET wafers in this study were grown at the same substrate temperature of approximately 600 C. The molecular beam pressure ratio of As to Ga was kept constant at 20 to 1 for all growth rates.

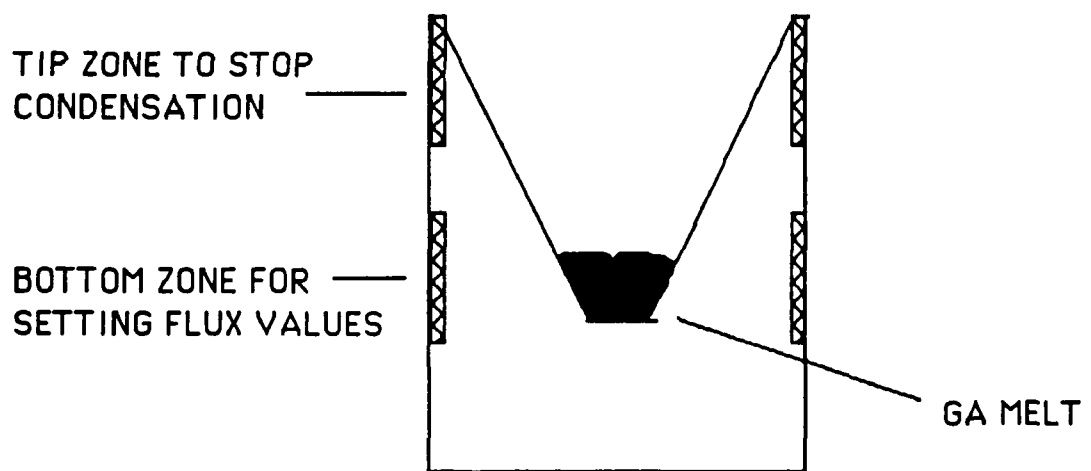
The epitaxially grown material was inspected under an interference contrast microscope for surface defects, and cut into squares for Hall measurement testing. The Hall measurement determines the electron concentration and mobility. The electron mobility of MODFETs is a well established and documented technique for evaluation of the material quality. For a given electron concentration, the higher the mobility (measured at 77 Kelvin), the higher the quality of material.

The baseline wafer had about 400 oval defects/ $\text{cm}^2$ , an electron mobility of 90,000  $\text{cm}^2/\text{V-s}$  at 77 Kelvin, and an electron sheet charge of  $1.0 \times 10^{12} \text{ cm}^{-2}$ . These are characteristic values for MBE material. Another sample was grown with the growth rate of GaAs being 2.0  $\mu\text{m/hr}$  and AlGaAs growth rate of 2.59  $\mu\text{m/hr}$ . The electron mobility and sheet charge of the second sample were indistinguishable from the first sample, but the oval defect count was more than double at around 1000 oval defects/ $\text{cm}^2$ . High surface defect counts on material reduce the yield of monolithic integrated circuits and cannot be tolerated for most applications.

The reason for the increase in oval defect count was investigated and found to be consistent with existing literature. As shown in figure 1a, a Varian Ga effusion cell consists of Ga contained in a boron nitride crucible that is placed into a refractory metal filament heater. The higher the heater power the higher the Ga evaporation from the crucible. The Varian cell design allows the top of the crucible to extend out of the hot zone of the cell. This extension of the crucible cools enough that Ga vapor condenses there. Ga does not appreciably wet boron nitride and eventually droplets slide back into the hot melt. As the cool Ga slides into the melt, a spray of Ga metal results. This is referred to as "spitting". This spray of Ga metal deposits on the growing GaAs wafer surface and results in oval defect formation. At high growth rates, more condensation occurs (probably with larger droplets and more violent spitting), thus the defect count is higher and unacceptable.



1a) Standard Varian Single-Filament E-Cell



b) EPI Dual-Filament E-Cell used to reduce oval defect densities at high growth rates

Figure 1. Comparison between the 2 types of E-cell designs used during Phase I.

At this time on the program it was obvious that a new cell design was needed to grow device quality MODFETs at higher growth rates. A new Ga cell was acquired and calibrated; its basic design is shown in Figure 1b. The new cell uses two separate filaments for cell temperature control. The lower filament is used to control the heat to the Ga melt, thus controlling the Ga vapor effusion rate. The top filament is run hotter than the lower to eliminate Ga condensation.

The cell worked perfectly: Figure 2 shows the oval defect count on MODFET wafers grown at rates as high as 5  $\mu\text{m/hr}$ . The top filament stopped the condensation of Ga, thus allowing for high growth rates with low defect counts.

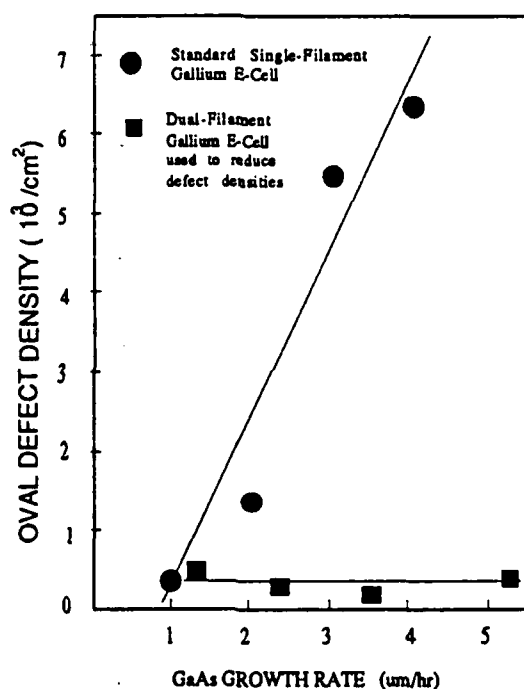


FIG. 2. OVAL DEFECT DENSITY AS A FUNCTION OF GaAs GROWTH RATE FOR BOTH SINGLE and DUAL-FILAMENT GALLIUM EFFUSION CELLS.

The wafers grown with this new cell were analyzed using the Hall measurement technique. The data are summarized in Table 1. The electron mobility ( $\mu_{77}$ ) shown in table one is a function of the sheet charge ( $N_{s77}$ ). If all of the layers had been doped to exactly  $1 \times 10^{12}/\text{cm}^2$ , the mobilities would have been identical, to the precision of the measurement. Even though the mobility seems to decrease slightly in the layer grown at the fastest rate of 5.2  $\mu\text{m/hr}$ , the sheet charge of this layer was high enough to account for this difference.

Growth rate ( $\mu\text{m/hr}$ ) sec)	Defects ( $\text{cm}^{-2}$ )	Rrt ( $\Omega/\text{cm}$ )	Ns77 ( $\text{cm}^{-2}$ )	$\mu 77$ ( $\text{cm}^2/\text{V}\cdot\text{sec}$ )
1.298	452	1000	$1.0\text{e}12$	88,000
2.349	293	970	$9.3\text{e}11$	90,000
3.496	200	900	$1.0\text{e}12$	86,000
5.236	400	950	1.2	74,000

This data clearly demonstrates that high electrical quality MODFET structures may be grown at growth rates as high as 5  $\mu\text{m/hr}$ .

Although the electron mobility measured in Phase 1 gives a strong indication that the material would make good FETs, further work is needed to address some of the more difficult device parameters that were beyond the scope of this program. The Phase 2 program will address these issues. Phase 2 will extend these material studies in the direction of high growth rate MESFET and MODFET material for MMIC processing and high growth rate GRINSCH-SQW material for Laser processing. Data from processed FETs and lasers will be correlated with growth rate to demonstrate the properties of the high growth rate material.

Phase 2 will grow MESFET and MODFET material to be made available to MIMIC contractors for device fabrication. The high growth rate laser material will be processed into laser diodes at Northeast Semiconductor.